

# Dissipation near the QCD phase transition

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We set up a framework for field theoretical studies of systems out of thermal equilibrium and zoom in on the dissipation of disoriented chiral condensates. Short relaxation times are obtained in the phase transition region, jeopardizing the definiteness of a DCC signal.

## 1. Introduction

QCD at finite temperature  $T$  and baryon density  $n_B$  is really hard to be tackled directly, except in two limiting cases: At very high  $T$  and/or  $n_B$  the coupling is weak allowing for perturbative calculations. At very low  $T$  and/or  $n_B$  the theory is strongly coupled, and chiral perturbation theory proved to provide a good description. In the nonperturbative region between these two limits effective field theories are needed. Such theories can be proved or disproved by experiments and lattice QCD simulations. Effective models incorporate only certain aspects of QCD, such as chiral symmetry. There is a phase transition between the above two limits, corresponding to symmetry restored and symmetry broken phases. We believe that as the matter produced at RHIC-Brookhaven National Laboratory [1] in the collision of ultrarelativistic heavy ions expands, it cools through this QCD phase transition. Experimental observations [2] suggest that the produced matter is almost baryon free. In the following, we discuss hot baryon-free matter. Cold dense quark matter phases are discussed in [3].

There are a large amount of models describing the chiral phase transition. The majority of these assume thermal equilibrium. RHIC results suggest though [4], that even if thermal equilibrium is achieved in some early stages of the collision, most probably it is not maintained as the matter rapidly expands and the temperature quickly drops below the transition temperature. The dynamical evolution of such an out-of-equilibrium system is not yet understood. When it comes to possible approaches, lattice simulations unfortunately do not prove to be the way to go, since lattice can describe static situations in thermal equilibrium. Therefore, one has to reside to different theoretical approaches.

A transition from ordered to disordered phase is accompanied by the formation of condensates. Here we talk about the chiral condensate,  $\Phi = (\sigma, \vec{\pi})$ , parametrized using the variables of the sigma model. In the phase where chiral symmetry is restored the condensate vanishes  $\Phi = (0, \vec{0})$ . As soon as the system passes through the phase transition chiral symmetry is broken and the condensate evolves back into its true ground state  $\Phi = (f_\pi, \vec{0})$ . The temporary restoration of chiral symmetry may result in the formation of disoriented chiral condensates (DCC) [5]: As the system passes through the phase

transition configurations in which the condensate is oriented differently than the normal ground state can develop,  $\Phi = (v, \vec{\pi} \neq 0)$ . DCCs relax to the correct ground state through the emission of low momentum pions with an anomalous distribution in isospin space. Detecting fluctuations in the ratio of produced neutral pions compared to the charged ones can serve as a signal of DCC production. DCC signals have not been observed at CERN-SPS. The STAR detector at RHIC searches for dynamical fluctuations on an event-by-event basis and may be therefore better suited for DCC searches.

The ability to detect DCCs depends on their lifetime. The original work [5] assumes a total quench scenario, meaning that at the critical temperature long-wavelength chiral fields completely decouple from the thermal background. In heavy ion collisions production of pions with high momenta is significant [2]. The effect of these thermal degrees of freedom should not be neglected. If energy exchange between the condensate and the heat bath becomes possible decay channels open up and scattering occurs. These processes are responsible for the dissipation of the non-equilibrium condensate, and thus the reduction of the lifetime of DCCs. Early estimates predicted 1 fm/c [6]. More recent calculations yield 4 – 7 fm/c [7]. We determine the lifetime of DCCs formed within a heat bath of mesons [8], developing a consistent semi-classical description of the chiral condensate out of thermal equilibrium. Some other related works are [9–11].

## 2. The theory

For studying DCCs the linear sigma model proved to be convenient framework. We decompose the fields into a non-equilibrium condensate and fluctuations about it. We do this by separating the different Fourier components of the fluctuation introducing a momentum scale  $\Lambda_c$

$$\Phi(x) = \bar{\Phi} + \Phi_s(x) + \Phi_f(x). \quad (1)$$

$\Phi_s = (\sigma_s, \vec{\pi}_s)$  are the long wavelength modes of the chiral order parameter,  $\langle \Phi \rangle = \bar{\Phi} + \Phi_s$ , slowly varying fluctuations, representing modes with momentum  $|\vec{k}| < \Lambda_c$ . These soft modes are occupied by a large number of particles and may then be treated as classical fields.  $\Phi_f = (\sigma_f, \vec{\pi}_f)$  are high frequency modes with  $|\vec{k}| > \Lambda_c$ . These hard modes, represent quantum and thermal fluctuations, and constitute a heat bath. By having nonzero pion condensate,  $\vec{\pi}_s \neq 0$ , we allow for the presence of DCCs. The equilibrium chiral condensate is chosen to lie along the sigma direction  $\bar{\Phi} = (v, \vec{0})$ .

We have derived classical effective equations for the non-thermal condensate,  $\Phi_s$ , embedded in the thermal background. The effect of  $\Phi_f$  is taken into account perturbatively, and improved with resummation. We coarse-grained these equations, which means that we averaged these over time and length scales that are short compared to the scales characterizing the slow fields, but long relative to the scales of the quantum and thermal fluctuations. Accordingly,  $\langle \Phi_f \rangle = 0$ , but quadratic terms and cross-correlations are nonzero. The non-equilibrium fluctuations we define as the sum of equilibrium fluctuations and deviations from this:

$$\langle \Phi_f^i \Phi_f^j \rangle = \langle \Phi_f^i \Phi_f^j \rangle_{eq} \delta_{ij} + \delta(\Phi_f^i \Phi_f^j), \quad (2)$$

where  $\delta(\Phi_f^i \Phi_f^j)$  are the responses of the heat bath to the presence of the condensate. Assuming the system is slightly out of equilibrium,  $\delta(\Phi_f^i \Phi_f^j)$  are determined using linear

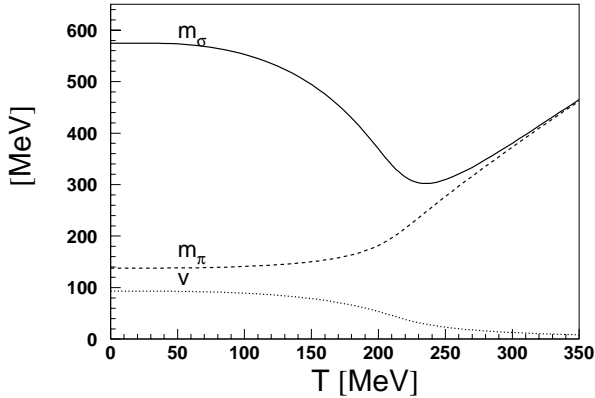


Figure 1. Temperature dependence of the resummed meson masses and of the equilibrium condensate.

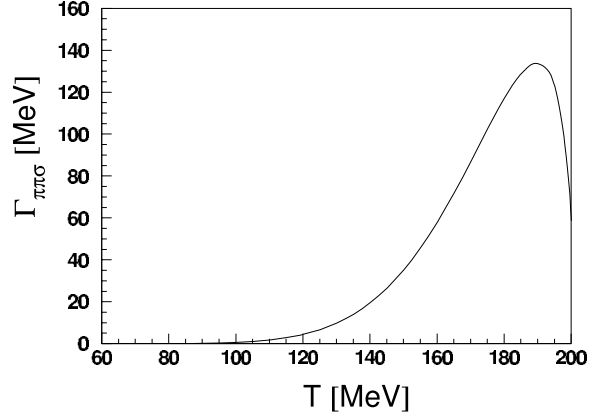


Figure 2. Temperature dependence of the pion damping rate due to  $\pi_s \pi_f \rightarrow \sigma_f$ .

response theory. The presence of linear response functions in the equations of motion is crucial: They renormalize the meson masses, change the velocity of propagation of the soft modes, and also introduce dissipation. Further details are found in [8].

### 3. Results

One-loop self-consistent numerical solutions for the meson masses and the equilibrium condensate are shown in figure 1. The equilibrium condensate monotonically decreases with increasing temperature. A crossover region can be defined where the sigma and pion masses start to approach degeneracy, signalling approximate symmetry restoration.

A soft pion from the condensate can annihilate with a hard thermal pion producing a hard thermal sigma meson,  $\pi_s \pi_f \rightarrow \sigma_f$ , provided  $m_\sigma \geq 2m_\pi$ . The temperature dependence of the net rate of dissipation,  $\Gamma_{\pi\pi\sigma}$ , is shown in figure 2. At  $T = 0$  the dissipation is zero, because this is exclusively a finite temperature process. At low  $T$  the available phase space is suppressed by the large sigma mass. With increasing  $T$  the sigma mass is dropping and the width of the pions is increasing. At  $T \simeq 170$  MeV, for example, the damping is about 55% of its energy. Dissipation of DCCs can also arise from scattering of soft pions with thermal pions  $\pi_s \pi_f \rightarrow \pi_f \pi_f$ , or thermal sigmas,  $\pi_s \sigma_f \rightarrow \sigma_f \pi_f$ . The damping rates are shown in figure 3. Again, at low  $T$  there is a strong suppression due to the heavy sigma exchange. With increasing  $T$  the scattering rate,  $\Gamma_\pi$ , grows comparable to  $\Gamma_{\pi\pi\sigma}$ . In the critical region the contribution from pion-pion scattering grows rapidly reaching a maximum at  $T = 200$  MeV. This is the same temperature as where  $\pi_s \pi_f \rightarrow \sigma_f$  becomes forbidden by the kinematics.

The rate at which equilibrium is approached is directly controlled by the damping through the relation

$$t = \frac{1}{\Gamma_{\pi\pi\sigma} + \Gamma_\pi} \quad , \quad (3)$$

and is presented in figure 4. In the phase transition region the decay time is the smallest. At  $T = 200$  MeV we found  $t = 0.17$  fm/c, and at  $T = 235$  MeV  $t = 1.36$  fm/c. When

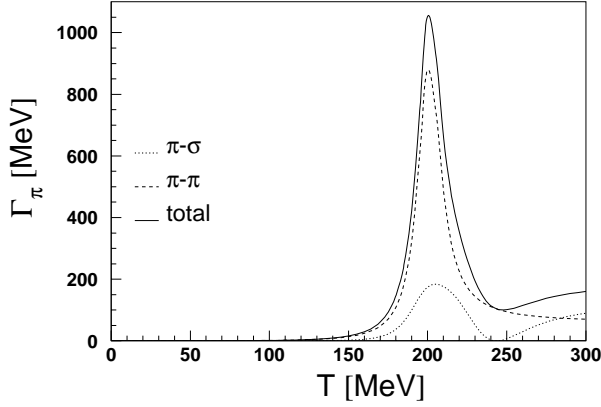


Figure 3. Temperature dependence of the pion damping due to  $\pi_s \pi_f \rightarrow \pi_f \pi_f$  and  $\pi_s \sigma_f \rightarrow \sigma_f \pi_f$  scattering.

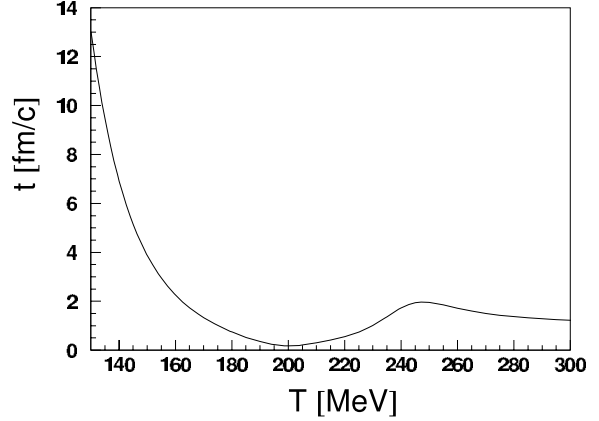


Figure 4. Temperature dependence of the relaxation time of homogeneous condensates.

assuming no multiple interactions with the heat bath then  $t$  is the lifetime of the DCC. The times we obtained are shorter than previous estimates [6,7], and are short enough to make possible DCC signals questionable. One can expect that multiple scatterings would further increase the damping, thus further decreasing the relaxation time.

#### 4. Summary and conclusions

Motivated by the survival possibility of DCCs in the background of a multitude of thermal particles formed after two heavy ions are collided at ultrarelativistic energies, we calculated the damping of the non-thermal chiral condensate. We found that not only decay but also scattering processes are significant dissipation sources. In the phase transition region short relaxation times were obtained, which makes the observation of a possible DCC signal questionable.

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